# Balance Velocities for the Greenland Ice Sheet

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Short title: BALANCE VELOCITIES FOR THE GREENLAND ICE SHEET

**Abstract.** We present amap of balance velocities for the Greenland ice sheet. Theresolution of the DEM, which was derived from the radar altimeter data, yields fargreater detail than inearlier balance velocity estimates for Greenland. The velocity contours reveal in striking detail the location of an ice stream in North Eastern Greenland, which was only recently discovered using satellite imagery. Enhanced flow associated with all of the major outlets is clearly visible. While errors in the source data yield errors in the absolute flow speeds, the balance velocity map appears to accurately locate areas of enhanced flow. Such data are extremely useful for modeling, mass balance studies, and field planning.

# 1. Introduction

The coverage over the Greenland Ice Sheet by the satellite-borne ERS-1 radar altimeter has dramatically improved our knowledge of the shape of the ice sheet surface. In this paper we will show that this knowledge, when combined with estimates of ice thickness and accumulation, yields a surprising amount of insight into the ice flow in the interior of the ice sheet. While we are only producing an estimate of the vertically averaged velocity required to maintain continuity, the knowledge of the surface from altimetry is detailed enough to show accurately where flow is converging into streams and to show the locations of ice divides and drainage bound aries. This work is in some aspects a repeat of earlier efforts in Greenland by *Budd,* et. *al* [1982], *Radok et. al* [1982], and *Bindschadler et al [1989];* it represents an advance because of the greatly improved knowledge of the ice sheet surface.

Interferometric studies of ice motion over limited parts of the ice sheet interior [*Joughin et al,* 1996] required estimates of motion for tiepointing; this in turn led us to the initial calculation of balance velocities using an elevation model derived from ERS and Geosat radar altimetry [*Ekholm,* 1996] [*Ekholm et al., 1995].* The rich detail in the velocity fields calculated from this work was unexpected. The detailed patterns of concentrated flow, which are apparent when the elevation model is used to trace flow lines, are in a number of cases not evident in moderate to high resolution satellite imagery of the ice sheet. We have found the balance velocity map to be useful for understanding ice flow patterns, for working with interferometric data, and for planning locations of field measurements.

# 2. Data And Technique

The balance velocity is the depth averaged velocity necessary to maintain the steady-state shape of an ice sheet *[Paterson, 1994]* [*Budd and Warner, 1996].* Thus,

for agate of width $L$ oriented normal to the flow direction, balance velocity can be calculated as

$$v_b = \frac{\int_{A_L} b \, dS}{\int_{-\frac{L}{2}}^{\frac{L}{2}} T \, dx}$$ **(1)**

where $b$ is the local mass balance, $T$ represents ice thickness, and $A_L$ is the upstream catchment area of the gate. *Radok et al* [1982] used a numerical method for computing the balance velocity along flow lines. Here we adopt a more brute-force approach. At each point on a 2-km grid we used a gate of width $L = 8$ km and plotted the flow lines upstream from both sides of the gate to bound the area $A_L$. We then applied Equation (1) to determine the balance velocity for each point. We smoothed the results using a 6-km-by-6-km moving average filter to obtain the final result, which is shown in Plate 1.

Our initial estimates of area where biased by the contributions from flow lines that were spaced less than a pixel apart in divergent areas near the summit. We resolved this problem in two ways. First we used a finer grid (0.5 km) for the flow line and area computation. Second, we weighted the pixels were the flowlines were one pixel apart with a heuristically derived weighting function to reduce their contribution in the area computation. After taking these measures, our area computations were biased by less than 1 per cent.

In applying Equation 1 three sources of data are needed: surface elevation, bedrock elevation, and local mass balance. From surface and bedrock elevation we are able to compute ice thickness. Surface elevation data were obtained from the KMS DEM [*Ekholm,* 1996], which is derived from GEOSAT and ERS-1 satellite altimetry, GAP airborne altimetry, and local survey. Airborne altimetry data were used to reduce long wavelength errors in the satellite altimetry along the sloping sides of the ice sheet.

Flow direction can be estimated from the direction of maximum averaged (over 10-20 ice thicknesses) downhill slope [Paterson, 1994]. We smoothed the KMS DEM

with a 20 km moving-average filter and determined the flowlines for our balance velocity calculations by following the direction of maximum slope. We also used the flowlines to determine drainage divides for many of the major outlet glaciers, which are shown in Plate 1. Divides were determined by selecting flowlines that passed through minima in the balance velocity field near the outer margins of our estimate.

The bed elevation was computed from Technical University of Denmark ice penetrating radar flights over the ice sheet [ *Gudmandsen, 1970].* The bed DEM was coarsely sampled and is, along with accumulation, one of the more poorly know parameters. A short discussion of the error sources and their influence on this type of estimation can be found in *Bamber et al.* [1996].

Local mass balance is the difference between the local accumulation and ablation. A comprehensive listing of accumulation data from pits, cores, and meteorological stations has been published by *Ohmura and Reeh [1991].* We interpolated this data to a regular grid for the balance-velocity computation. We limited our estimates of velocity to the area where the ice thickness is greater than 1200 m. Because ablation is typically small for this region, we could use the re-gridded accumulation data as a proxy for the local mass balance. While ignoring ablation may lead to some error in the lower lying and southerly regions covered by the velocity map, we expect such errors to be small as the majority of the upstream catchments feeding these areas have negligible melting and runoff (i.e., they lie in the upper percolation facies or dry snow facies). Limiting the velocity estimates in this way also allowed us to avoid problems with DEM accuracy in the highly sloping regions on the perimeter of the ice sheet, where satellite radar altimeters have difficulty tracking.

## 3. Discussion

While Plate 1 contains a wealth of information, the most notable characteristic is the detail in the structure of contours of balance speeds and drainage boundaries in

the interior of the ice sheet. This detail in the contours is primarily a result of features in the elevation model used to determine ice flow direction and to a lesser extent is influenced by ice thickness and accumulation patterns.

In this figure it is clear that the ice flow in northeast Greenland departs significantly from the patterns seen in the rest of the ice sheet. Here a number of channels of enhanced flow begin well into the ice sheet interior, and reach speeds that elsewhere only occur much closer to the ice sheet edge. The large ice stream in northeast Greenland [*Fahnestock et al., 1993*] stands out clearly; it shows much more structure in the interior than is evident from visible and SAR imagery of the area. In high resolution imagery it appears to have a single tributary that flows essentially straight along the course of the middle part of the stream; in the balance map it is shown with a second tributary of comparable speed flowing in from the south. We have seen preliminary evidence in SAR interferograms that this feature exists as predicted by the balance velocities. Just to the east of this second tributary is another flow feature that reaches well in from the coast, initially flowing northeast and bending around to flow out Waltershausen Glacier.

From this point, as we move south along the east coast, the drainages are highly convergent on large outlet glaciers and have good-sized interiors. The glaciers on the east coast have very steep gradients and flow through large, well established fjords. This produces the branching nature of the drainage divides in this area.

On the west coast, this pattern gives way to a more ordered pattern, where the drainages have nearly parallel sides reaching up to the divide. The Jakobshavns Isbrae drainage breaks from this pattern, with at least three branches converging near the coast. There are a few other large glaciers to the north of Jakobshavns Isbrae, with rapid flow seen for Rinks Isbrae, several drainages to the north of Upernavik, and one just south of Camp Century.

The pattern of ice flow changes character again in the north, where Petermann Glacier dominates the drainage, with rapid flow well into the ice sheet; the flow speed

in Petermann is substantially greater than what is seen in Humboldt (the 100 km wide glacier juts to the south-west). Qualitatively the balance velocity on the Petermann agrees well with the interferometrically measured velocity field [*Joughin et al,* in preparation]. The predicted location of rapid flow matches the interferometric data well. The velocity along the center line of the glacier, however, exceeds the actual velocity. This is because the resolution of the bed DEM is not sufficient to resolve the channel underlying the Petermann. Because the assumed ice thickness is thinner than it actually is, continuity dictates that the estimated speed should be greater than the true speed. This phenomenon likely influences the estimates of flow speed on other outlet glaciers with well developed channels missed in the bedrock DEM.

The pattern of ice flow, shown here as balance velocities, reveals a significant amount about the current behavior of the ice sheet. While these velocities assume steady state, and are subject to error from sparse accumulation data and limited ice thickness information, the pattern of flow is determined by the surface elevations and should be an excellent reflection of reality.

As our understanding of the shape of the ice sheet improves, we learn a substantial amount about the current ice flow. Much of what we see in an elevation model confirms recent observations about discharge; some of what can be learned from the elevation model provides new insight. Each improvement increases the challenge for numerical models of ice sheet behavior; it also improves the boundary conditions needed for this work.

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**Plate 1.** Balance velocities and drainage divides for the Greenland ice sheet plotted over ERS-1 SAR mosaic.